Space Technology 5

"Paving the Way for Future Micro-Satellite Missions"

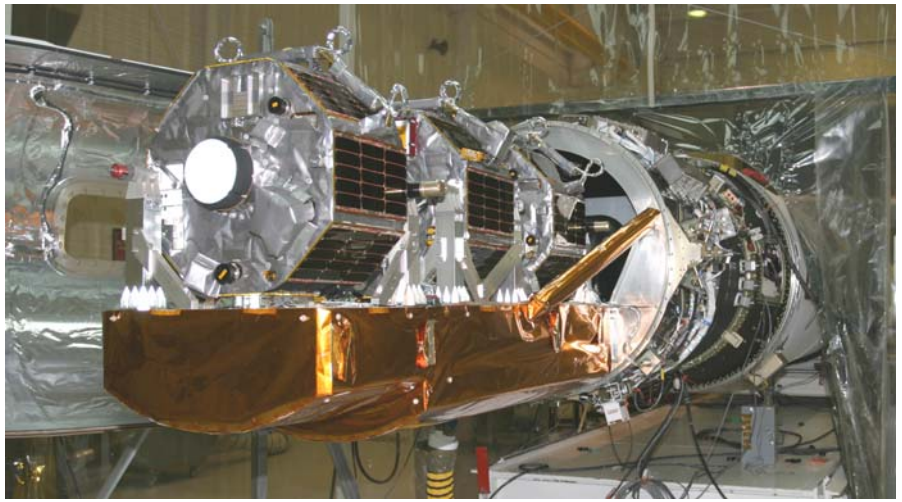
Space Technology 5

Technology and Constellation Validation

Candace Carlisle, ST5 Deputy Project Manager
Guan Le, ST5 Project Scientist
Goddard Space Flight Center

ST5 Mission Overview

- **NASA New Millennium Program mission to flight-validate new concepts and technologies**
  - Designed, built and operated three 25 kg spacecraft utilizing breakthrough technologies
  - Demonstrated the ability to achieve accurate, research-quality scientific measurements utilizing a constellation of 3 micro-satellites
  - Operated the three satellites as a single Constellation



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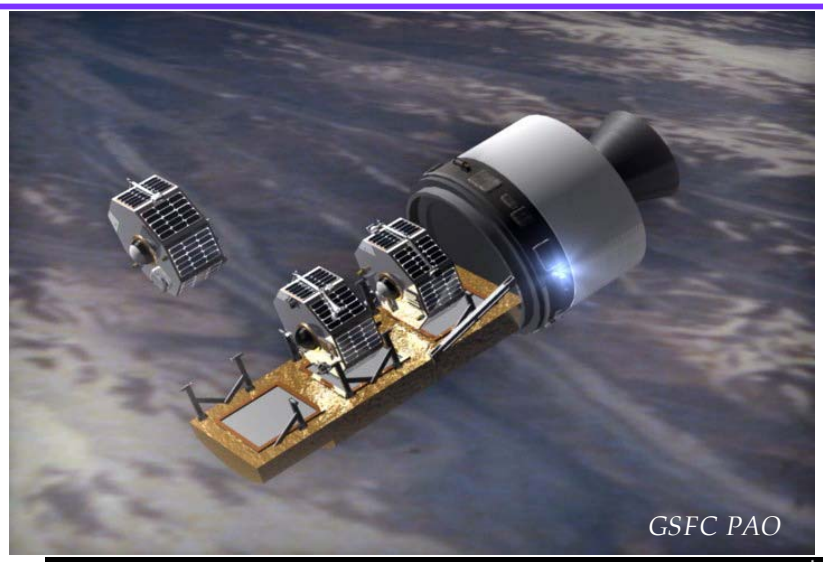
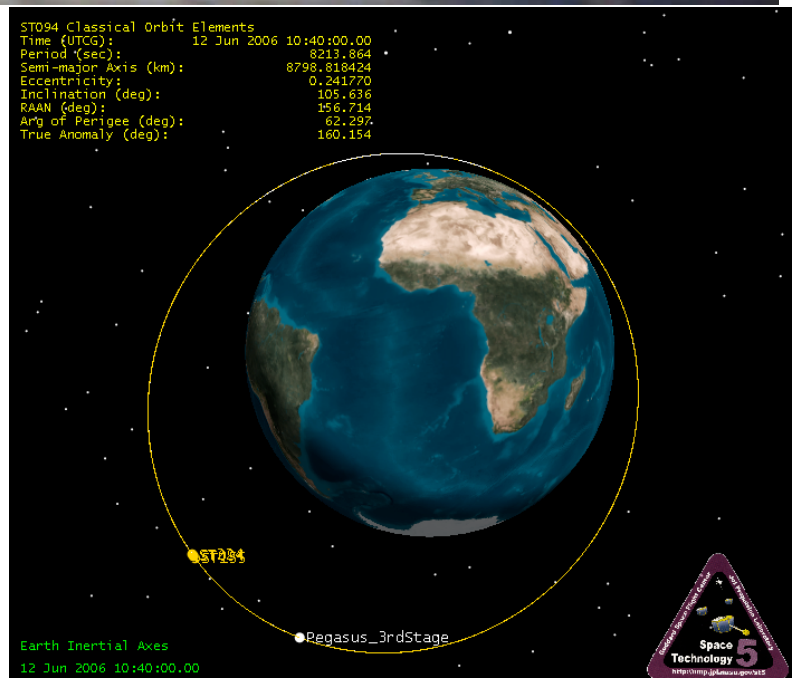
ST5 Mission Profile

- **Launched March 22, 2006**
  - Pegasus out of Vandenberg
  - Approximately 10 min after launch, ejected 3 min apart Frisbee-style
- **Mission Duration: 90 days**
  - 7 day launch & early orbit period
  - Mission completed June 20, 2006
- **Orbit**
  - 105.6 deg inclination (full sun orbit)
  - ~300 km perigee; ~4500 km apogee
  - 136 minute period
- **Communications: Deep Space Network, McMurdo Ground Station**
- **Constellation Configuration: "String of Pearls"**

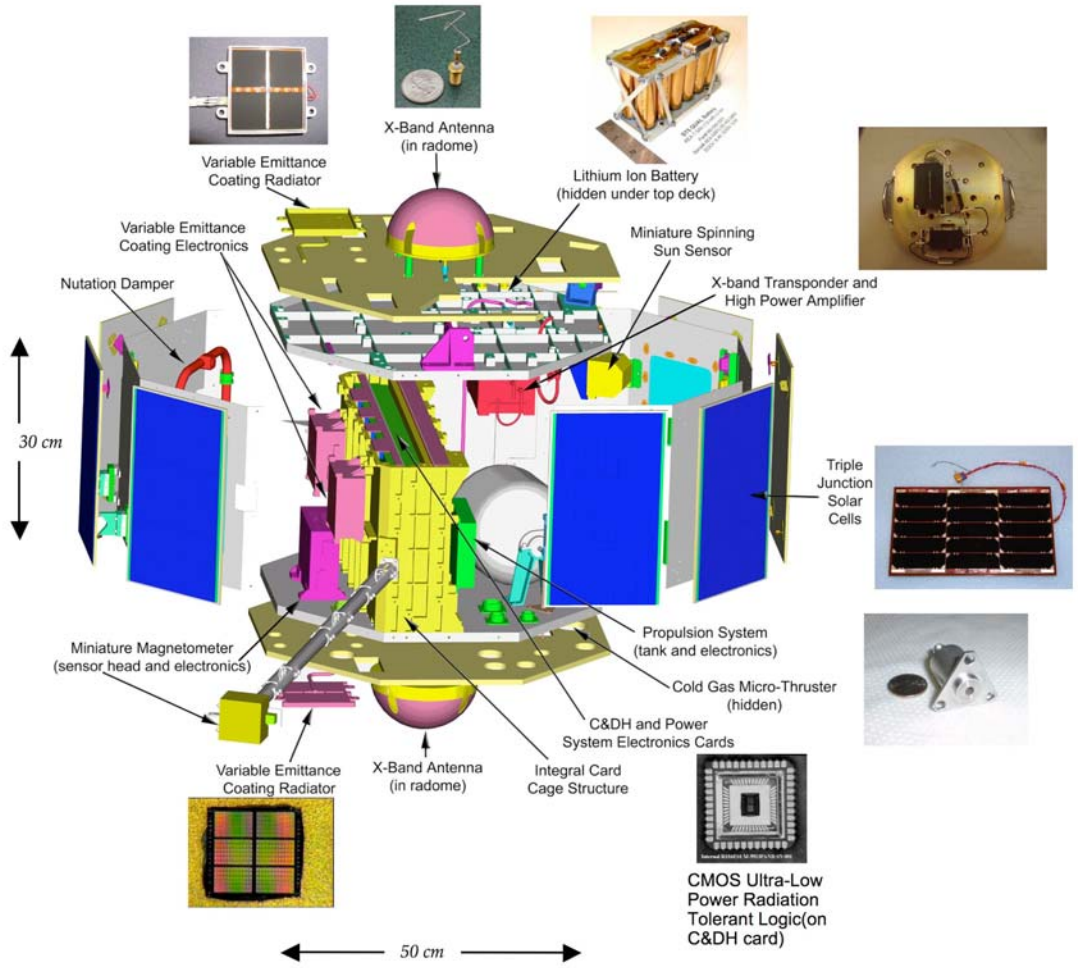




ST5 Spacecraft

- **Developed by GSFC**
- **Description**
  - Built within tight volume and mass constraints
  - Low-power and low voltage
  - ~50 cm x 48 cm
  - Integral card cage structure (for C&DH, PSE)
- **Key performance parameters**
  - Mass ~ 25 kg
  - Spacecraft-induced magnetic field effects as measured at the magnetometer sensor location less than 10 nT (d.c.), 5 nT (a.c.)
- **Science demonstration instrument**
  - Research-grade flux-gate magnetometer
  - High resolution, high precision, three-axis magnetic measurements
- **GSFC designed, built, tested and operated the spacecraft and deployment structure**
  - Partnerships with industry, other NASA centers and academia

ST5 Technologies

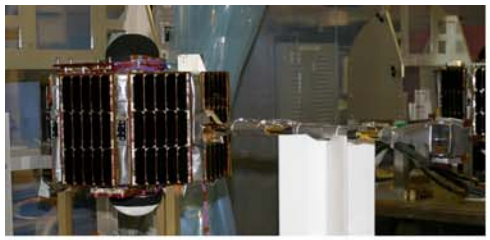


- **NMP Technologies**
  - Miniature transponder (AeroAstro)
  - Cold gas micro-thruster (Marotta)
  - Variable Emittance Coatings (APL, Sensortex, Sandia)
  - CMOS Ultra-Low Power Radiation Tolerant Logic (University of Idaho)
  - Low voltage power subsystem including Li-Ion Battery (Emcore, AEA)
  - Software tools for autonomous ground operations
- **Other technologies**
  - Miniature scientific-grade magnetometer (UCLA)
  - Miniature spinning sun sensor (Adcole)
  - X-band antennas (quadrifilar helix (New Mexico State University) and evolved (NASA Ames, NMSU))
  - Spacecraft deployment mechanism
  - Magnetometer deployment boom
  - Nutation Damper

Spacecraft and Component Technology Validation

- **Thoroughly tested on the ground**
  - Comprehensive funcational and performance testing at component and s/c level
  - Vibration and thermal vacuum testing of components and s/c
  - Measurement of magnetic signatures of components and integrated s/c
  - Ground calibration of magnetometer sensors
- **On-orbit demonstration**
  - Transponder used throughout the mission for command, telemetry, and radiometric orbit determination
  - Cold gas micro-thrusters used for attitude control and constellation maneuvers
  - Variable emittance coatings operated at regular intervals
    - Used a heater for calibration
  - CULPRiT used routinely for Reed-Solomon encoding
  - Low voltage power system used throughout the mission
  - Magnetometer data collected throughout the mission
  - Spacecraft clock maintained to 10 ms using return data delay and thermal model of oscillator performance

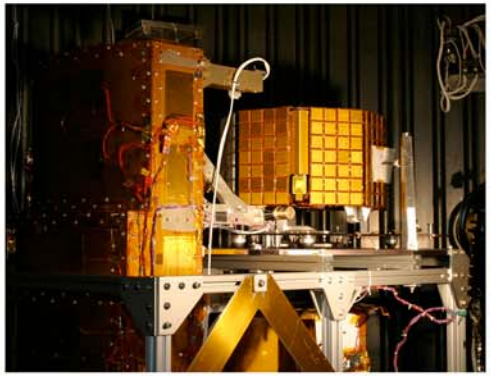
Integration and Test at GSFC



ST5 Spacecraft

Test deployment of flight spacecraft from Pegasus Support Structure

Pegasus Support Structure and Spacecraft Vibration Testing

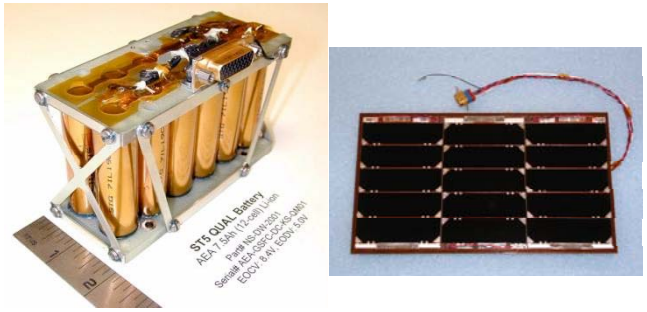


Test deployment from Pegasus Support Structure in Thermal Vac

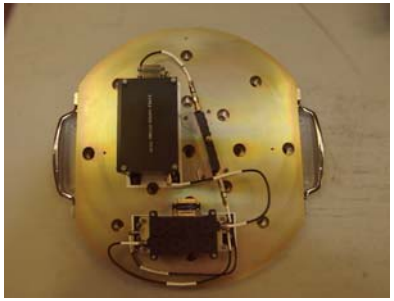
Spacecraft 2 and 3 in Thermal Vacuum Chamber

Final mass properties

ST5 New Millennium Program Technology Validation (1/2)



Low Voltage Power System

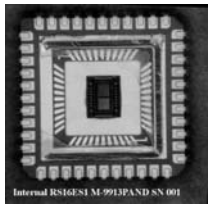


Transponder

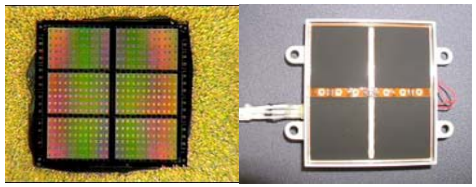
- **Power System incorporating a Lithium-Ion Battery and triple-junction solar cells: Provided s/c power**
  - Battery effective Capacity = 7.5A-h (to 6Vdc C/2 discharge)
  - Solar array beginning of Life Electrical output per panel (30°C, 1 Sun Air-Mass Zero): load voltage = 10.2Vdc, current = 1.16 amps
  - Triple junction Gallium Arsenide solar cells are the highest efficiency available to date, with average efficiency of 28.5%
  - ST5 power system performed well, supporting all mission operations at full power
  - Batteries performed well, remaining above 90% state of charge in normal operations
- **X-Band Transponder: Provided coherent uplink and downlink, and support for orbit determination**
  - Uplink rate 1 kbps; Downlink rate 100 kbps and 200 kbps.
  - Average bit error rate (BER) of less than 1x10-5 for each downlink pass.
  - Transponders and antennas performed flawlessly in 100 and 200 kbps downlink with McMurdo and DSN

ST5 New Millennium Program Technology Validation (2/2)

Micro-Thruster



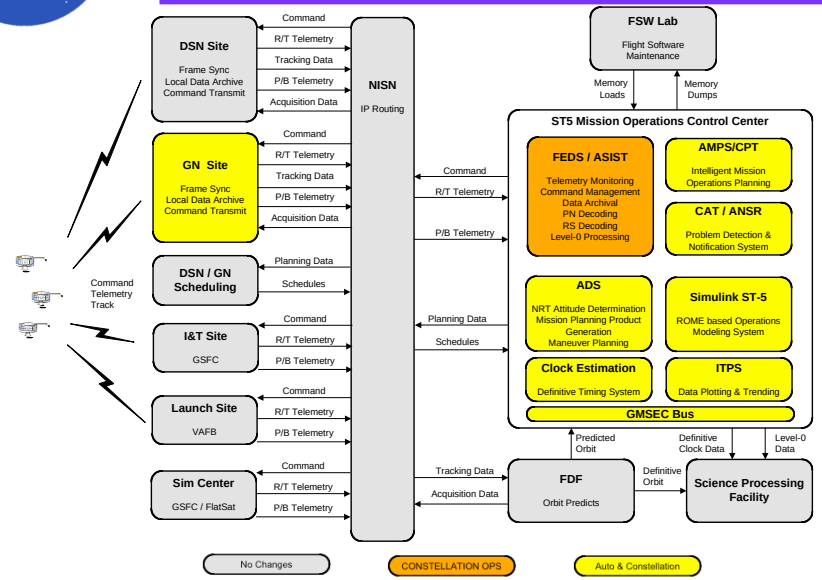
CULPRiT

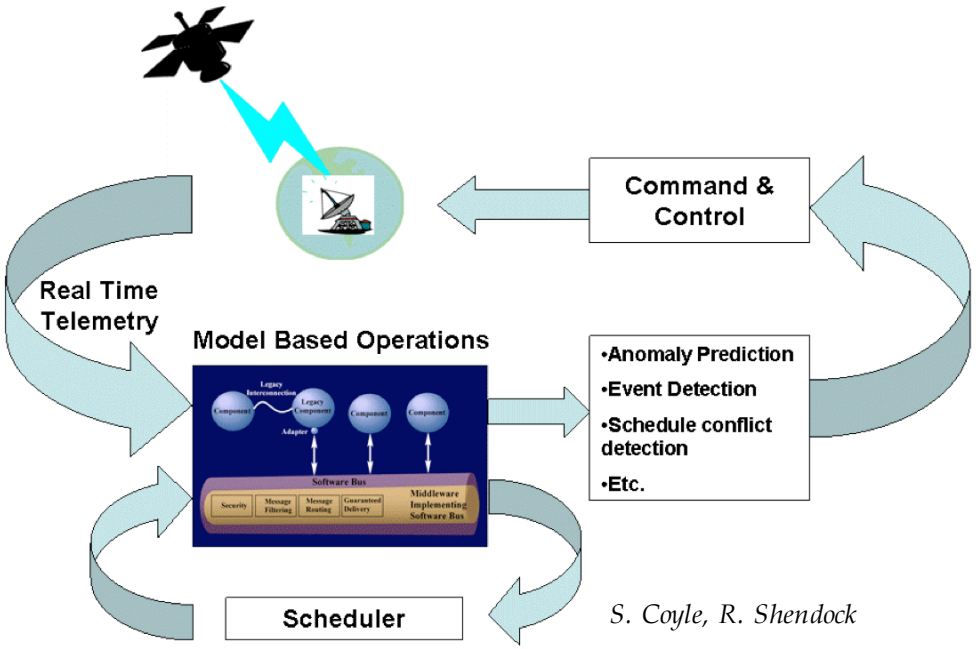


Variable Emittance Coatings

- **Micro-thruster: Used for attitude maintenance and Delta-V maneuvers to constellation formation**
  - Can be operated in pulse and continuous fire modes
  - Specific impulse greater than 60 sec.
  - Thrust greater than 2.1 N at 2000 psi, and greater than 0.1 N at 100 psi.
  - Successfully used for orbit and attitude maneuvers throughout the mission
- **Complimentary Metal Oxide Semiconductor, Ultra Low Power Logic (CULPRiT): Low-voltage CMOS technology**
  - Radiation and latch-up tolerant
  - Used as Reed Solomon encoder
  - Operating voltage of 0.5V
  - The CMOS Ultra Low Power Radiation Tolerant digital logic (CULPRiT) technology (0.5V) on all three spacecraft were error-free, while being exposed to hundreds of radiation events
- **Variable Emittance Thermal Coatings: Thermal control demonstration**
  - Range of emissivity variation 0.4 to 0.6
  - VECs performed well on orbit

Autonomous Constellation Operations

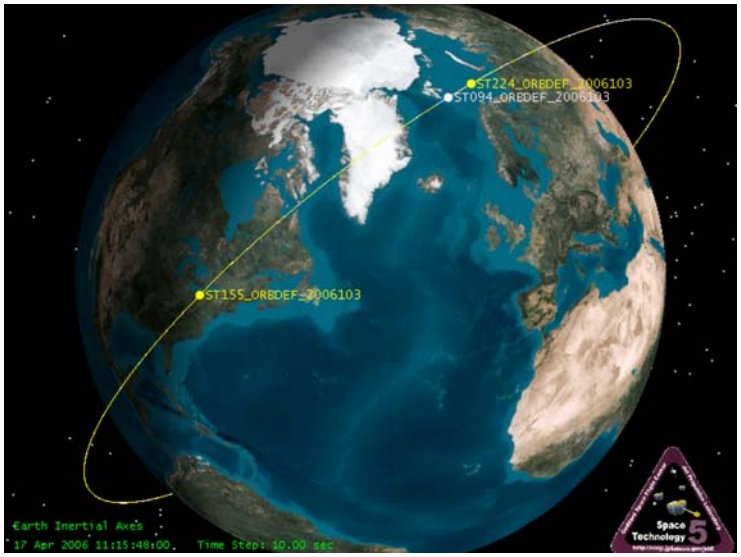




S. Coyle, R. Shendock

- **Operated multiple spacecraft as a single constellation**
  - Demonstrated concepts for autonomous constellation management and autonomous operations
  - Accommodated downlink and ground data processing of multiple data streams from multiple spacecraft
  - Performed model-based constellation health and safety management
  - Performed simulated “lights out” operations for one week (June 11-18, 2006)
    - Achieved ~81% data return (meeting 80% requirement) despite sub-optimal ground station visibility

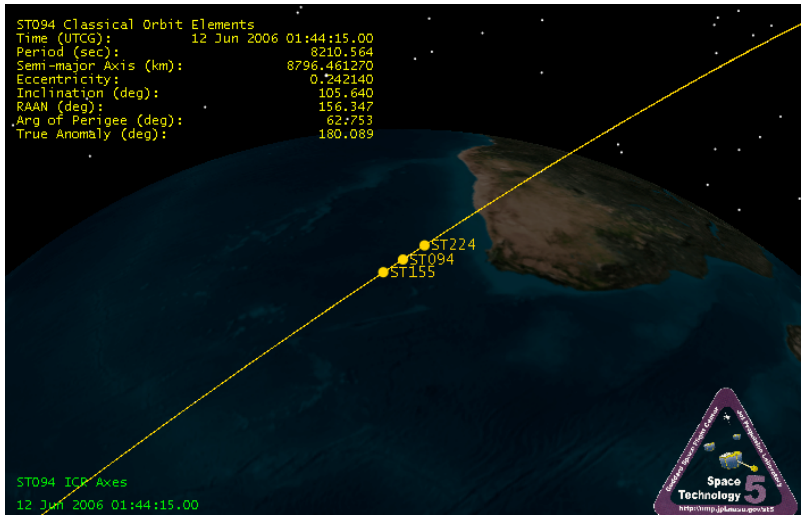
ST5 Constellation Formation



"Before": April 17, 2006

"After": June 12, 2006

Demonstration of ability to spatially configure the s/c in a geometry that supports the science validation requirements



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ST5 Maneuvers

Maneuver Name	Maneuver Date	Maneuver Date	Description
FWD ATT1	*2006/096*	*Thursday, April 6*	*Engineering burn to test attitude mode* *DV=0.03 m/s*
AFT ORB1	*2006/098*	*Saturday, April 8*	*STOP separation rate between AFT and reference s/c.* *DV=0.25 m/s*
FWD ORB1	*2006/104*	*Friday, April 14*	*STOP separation rate between FWD and reference s/c.* *DV=0.80 m/s*
FWD ORB2	*2006/111*	*Friday, April 21*	*START formation deployment, negative separation rate to bring in FWD closer to reference s/c* *DV = 0.66 m/s*
FWD ORB3	*2006/130*	*Wednesday, April 10*	*STOP (or SLOW) separation rate of incoming FWD s/c relative to AFT.* *DV = 0.62 m/s*
MID ORB1	*2006/138*	*Thursday, May 18*	*Change reference s/c to AFT. STOP separation rate between MID and AFT. Target mean in-track separation to AFT as 270 km.* *DV = 0.11 m/s*
FWD ORB4	*2006/145*	*Thursday, May 24*	*STOP (or TRIM) separation rate of incoming FWD s/c. Target mean separation to AFT as 320 km.* *DV = 0.33 m/s*
AFT ATT1	*2006/152*	*Thursday, June 1*	*TRIPLE PLAY : Decrease the magnitude of the sun elevation angle; Align spacecraft spin axis to be normal to the earth's magnetic field & "trim" overall spacecraft constellation.* *DV =0.4 m/s*
AFT ORB2	*2006/164*	*Tuesday, June 13*	*TRIM separation rate of AFT relative to MID to increase In-Track separation. Accounts for increased drag profile following AFT ATT1* *DV =0.10 m/s*

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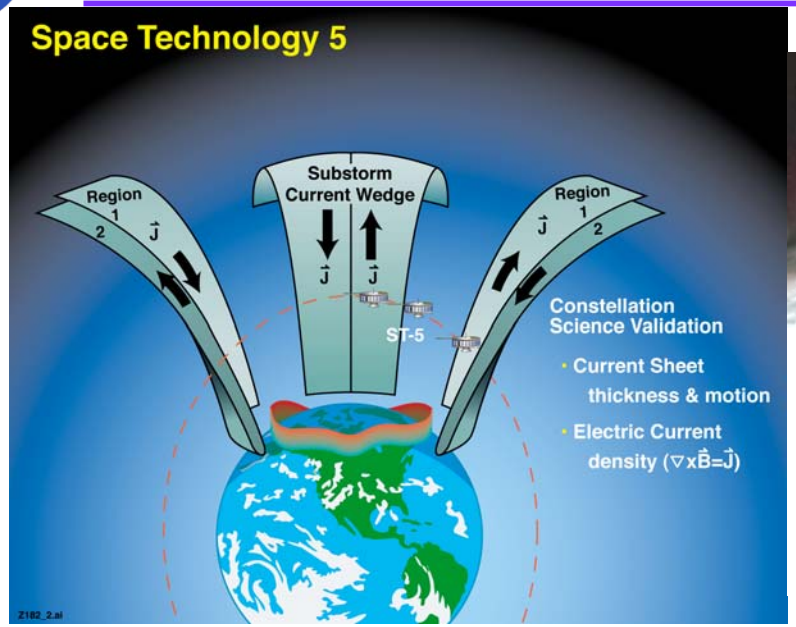
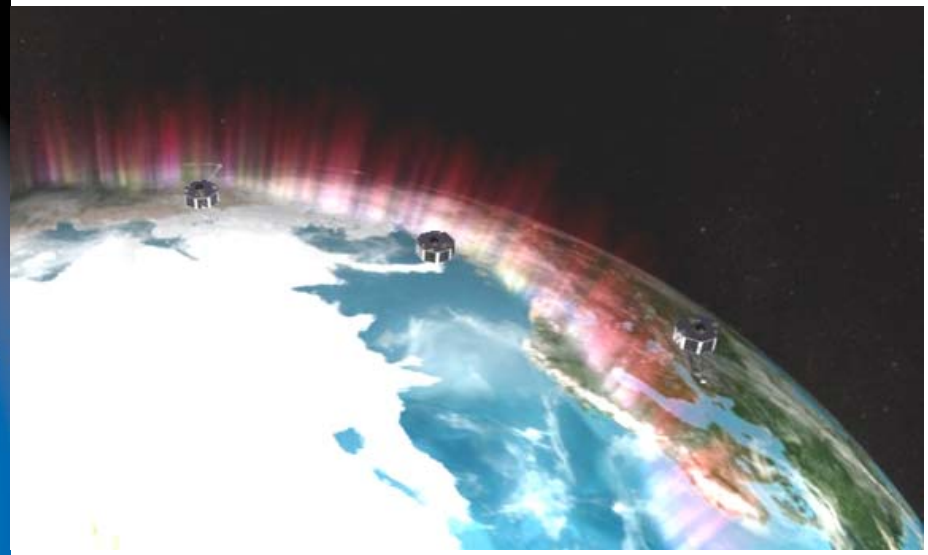
Research-quality Science Demonstration





GSFC PAO

•ST5 validated the constellation concept by the measurement of important physical parameters that cannot be determined by single spacecraft.

-Constellation configuration allows simultaneous multi-point measurements of magnetic field across auroral current sheets.

•Formation fly in pre-determined configuration over the Earth's northern and southern auroral zones (position uncertainty < 1 km)

•Returned research-grade magnetometer measurements from a suitable platform

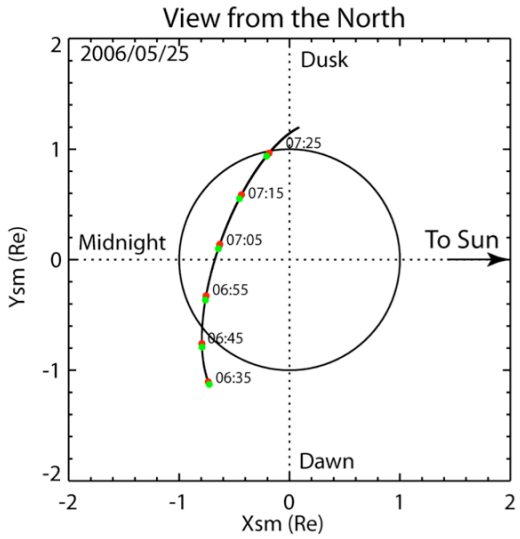
•Measured auroral current sheet motion and thickness, electric current density and temporal stability using the ST 5 constellation data

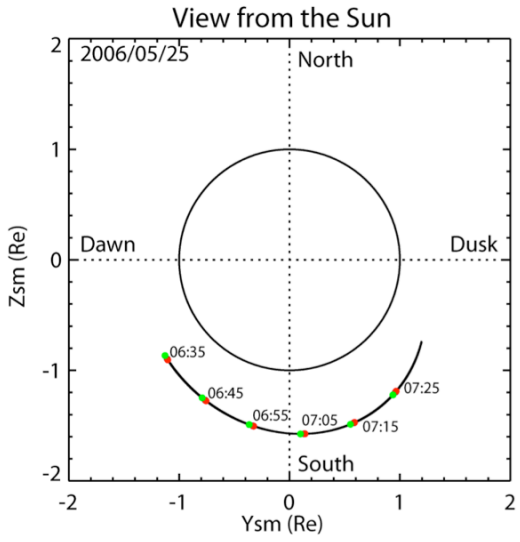
ST5 Science Validation Status

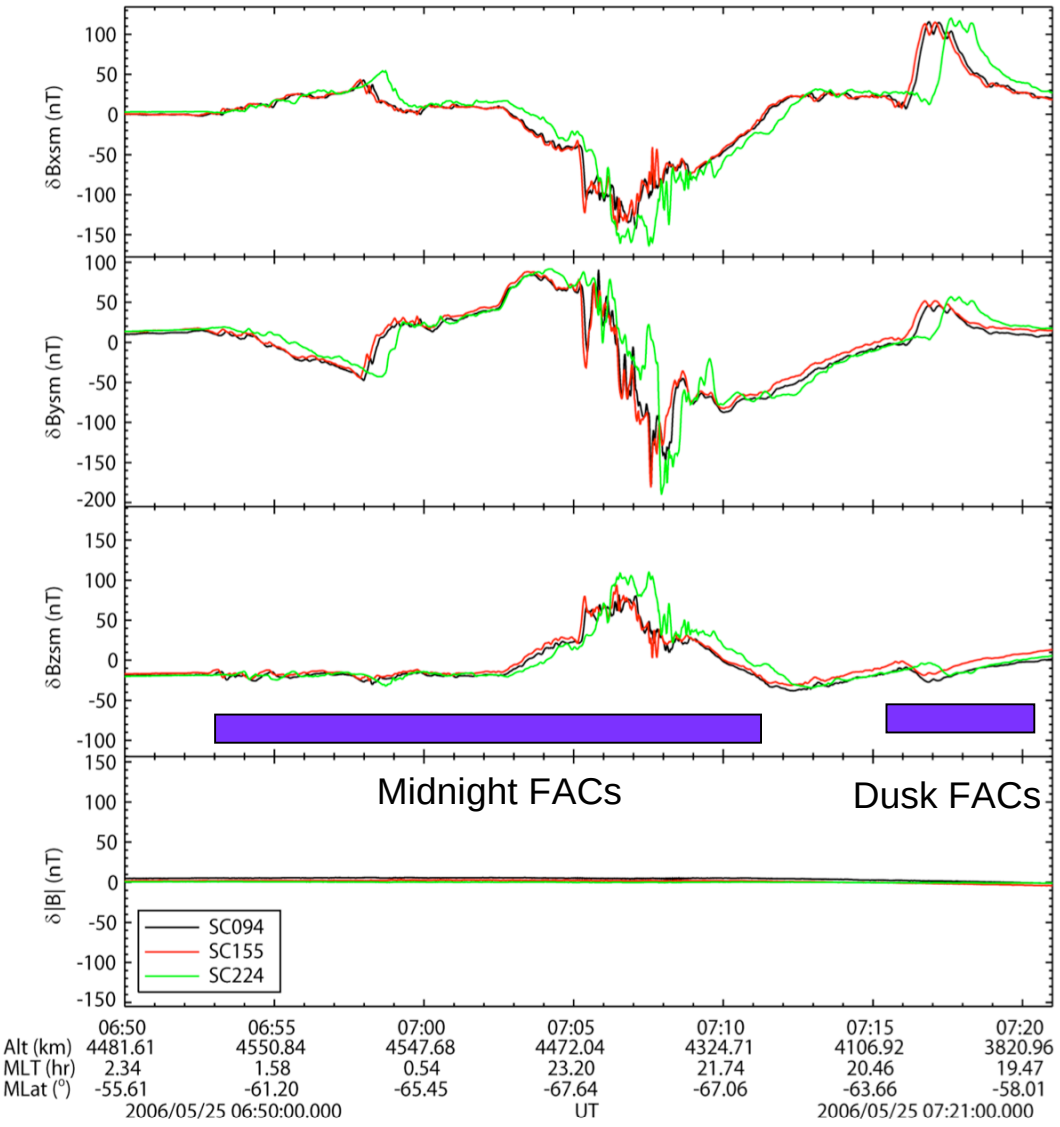
- **To date, we have processed the magnetic field data up to June 21**
  - Each spacecraft measures the vector magnetic field from a spinning-stabilized platform. The data processing involves calibrating and despinning the data into geophysical inertial coordinate systems.
  - Magnetic field data processing also requires the sun sensor data, spacecraft attitude data, and ephemeris data.
  - The results show that the ST5 magnetic field data are of very high quality. We do not see any contamination in the data due to spacecraft nutation or coning, and unstable spacecraft magnetic field.
- **ST5 constellation returned unprecedented data on the Earth's auroral currents as well as on the crustal magnetic field**
  - ST5 provided for the first time simultaneous multi-point measurements of auroral electric currents at low altitudes, which allow us to separate temporal and spatial variations of these currents.
  - ST5 provided a unique data set on the Earth's crustal magnetic field, which is a consequence of both the constellation flying, and the enhanced resolution from the low perigee, lower than any previous geomagnetism mission.

ST5 Observations of Auroral Field-Aligned Currents (FACs) – 1/2

Magnetic Field Generated by FACs at ~ 4500 km Altitude



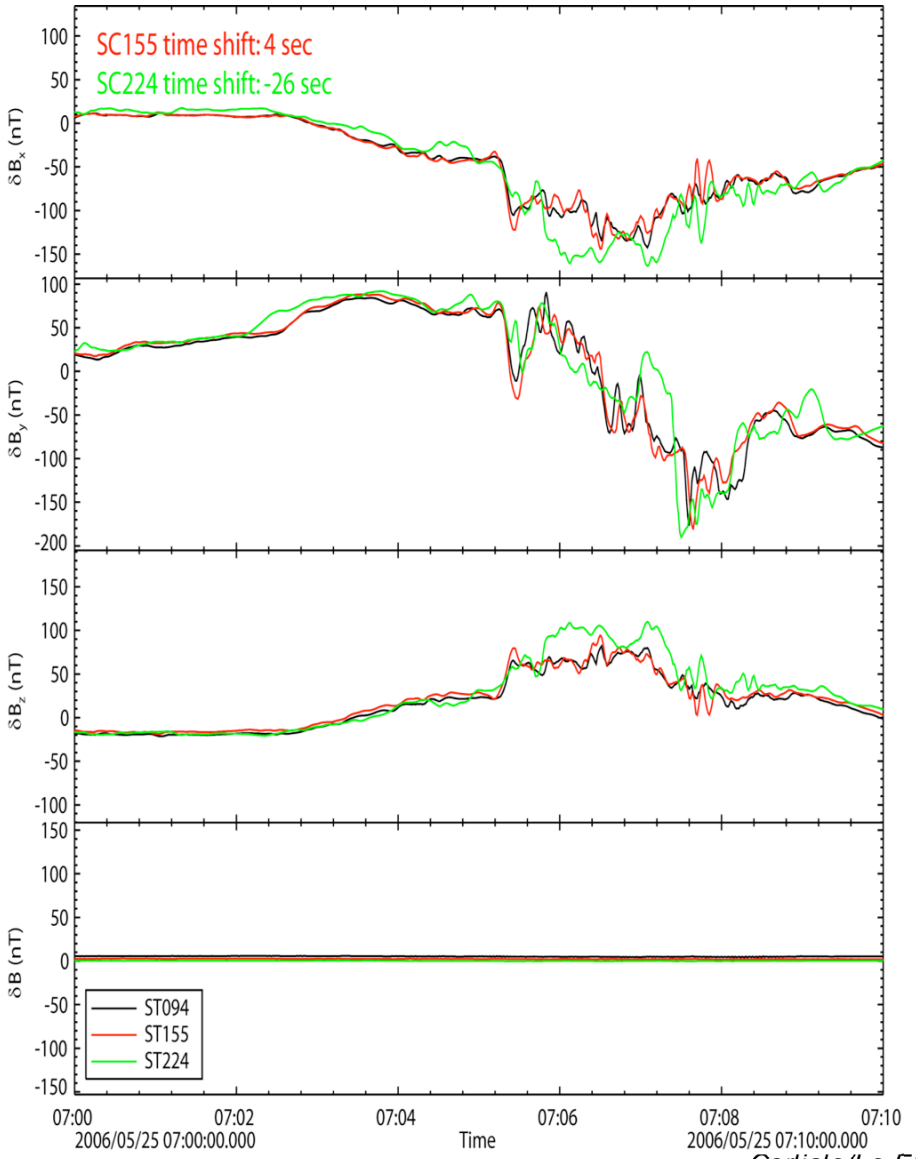




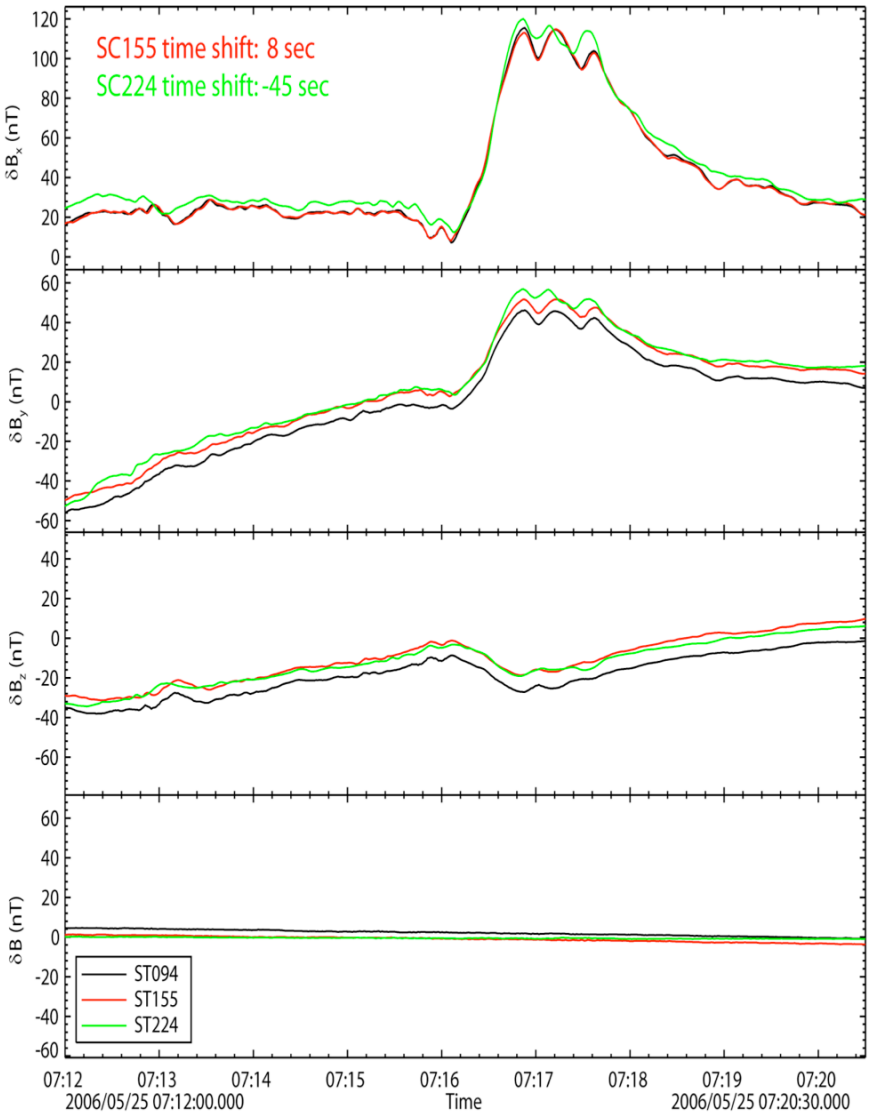
ST5 Observations of Auroral Field-Aligned Currents (FACs) – 2/2

Temporal Variations (~ 4500 km Altitude)

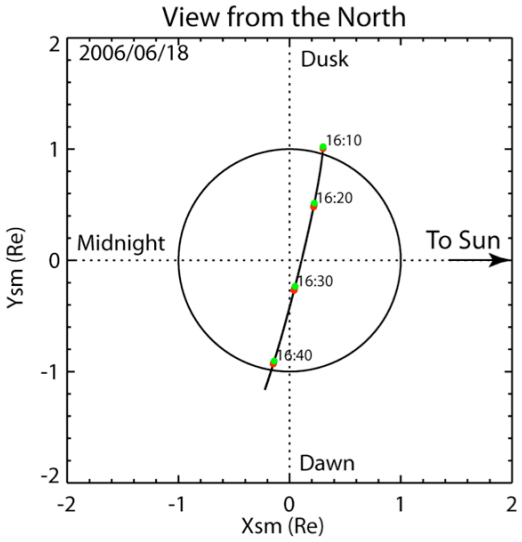
Midnight FACs

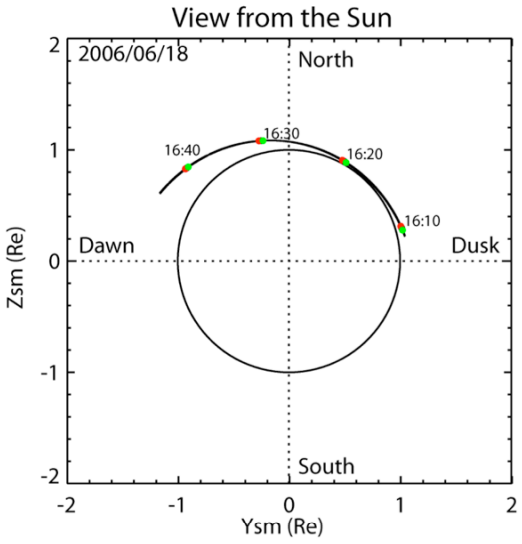


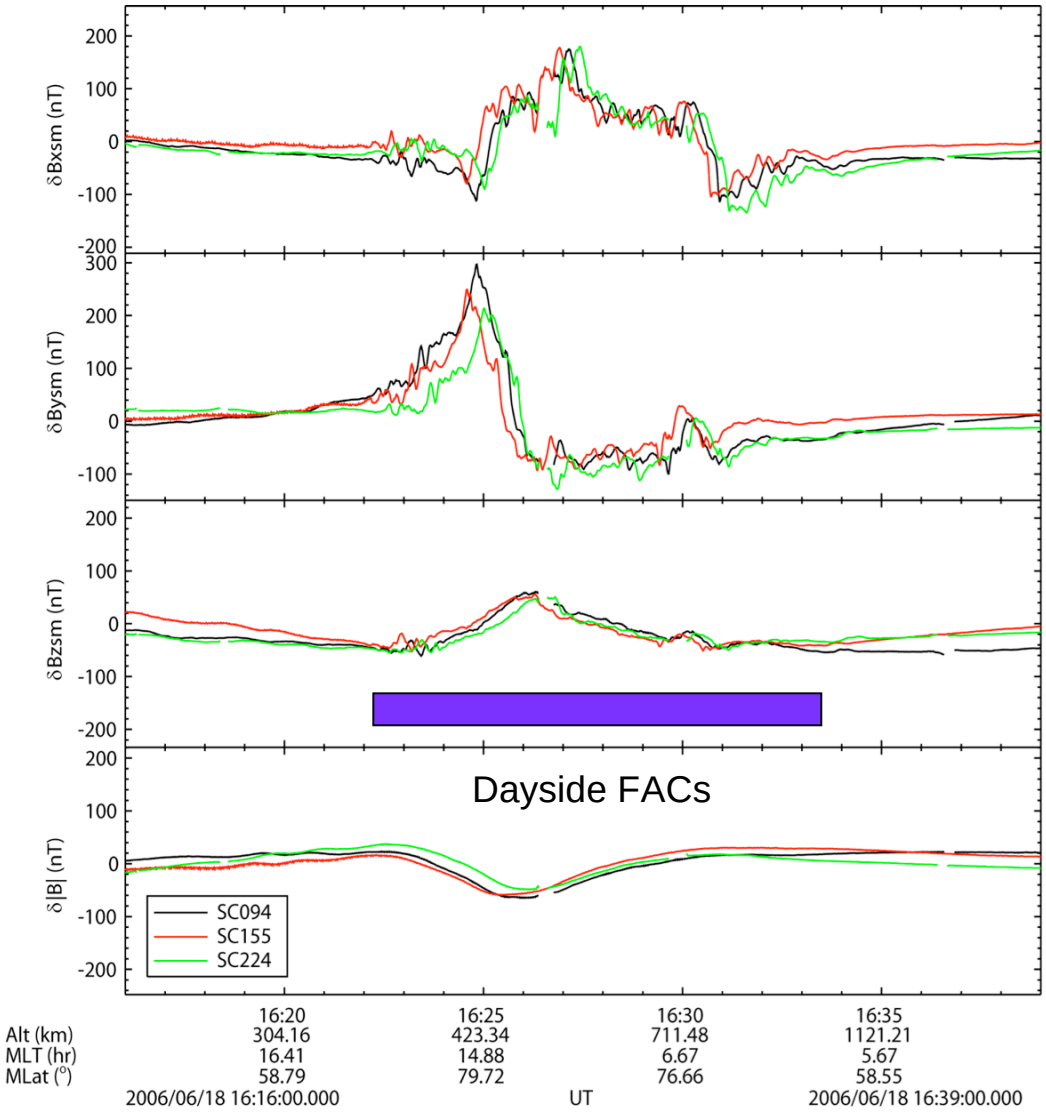
Dusk FACs



Magnetic Field Generated by FACs at ~ 500 km Altitude

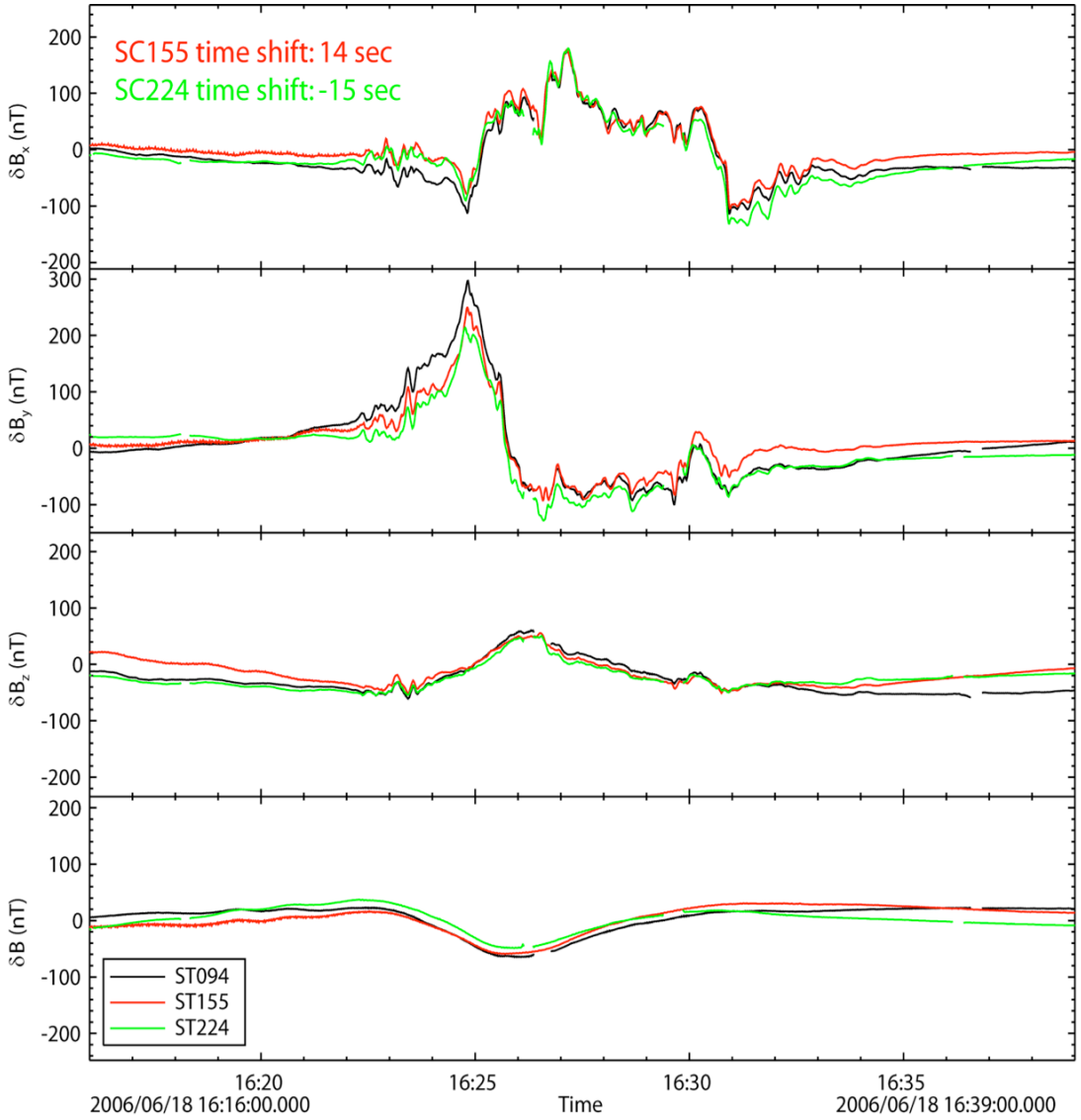






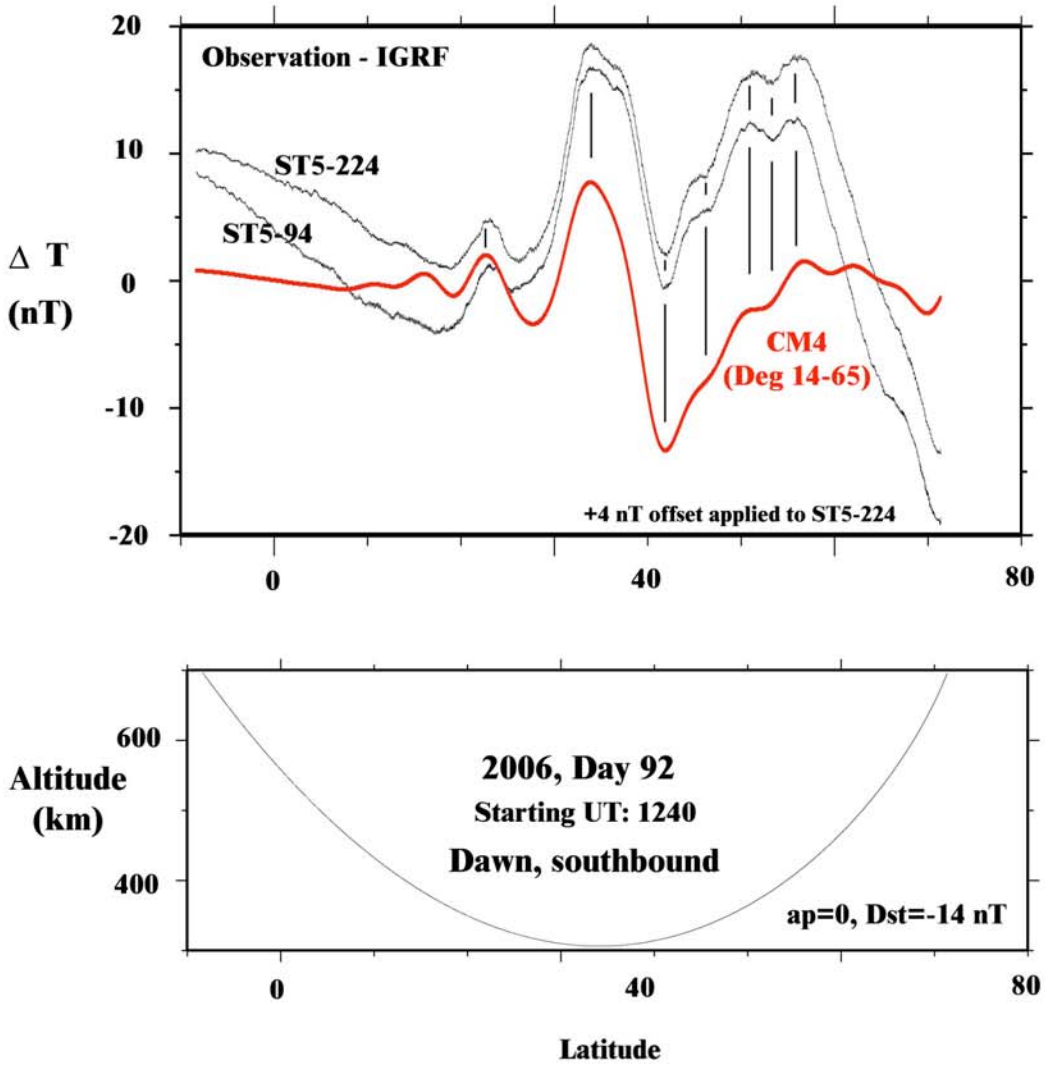
ST5 Observations of Auroral Field-Aligned Currents (FACs) – 2/2

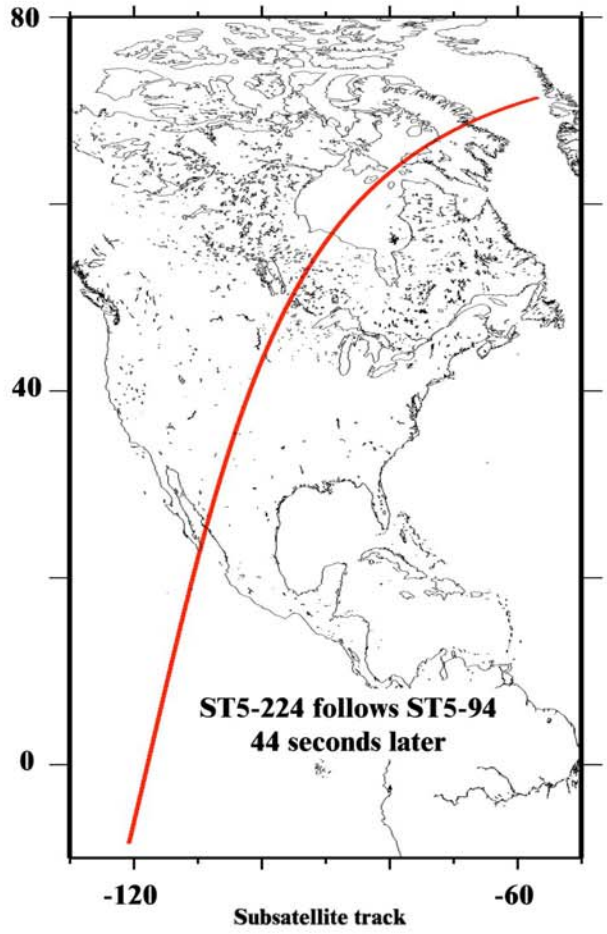
Temporal Variations (~ 500 km Altitude)



ST5 Observations of Magnetization of Earth's Crust – 1/2

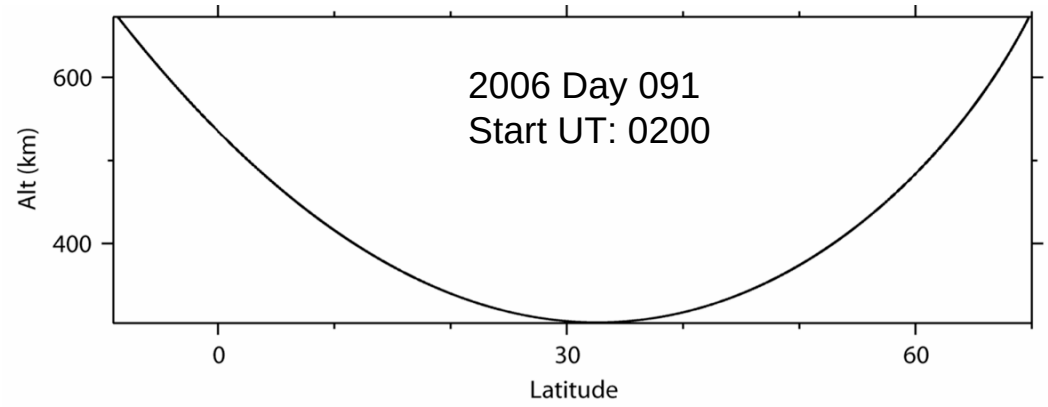
Crustal Magnetic Field - Comparison of ST5 Observations and the High-Degree Lithospheric Field Component of the Comprehensive Model (CM4)



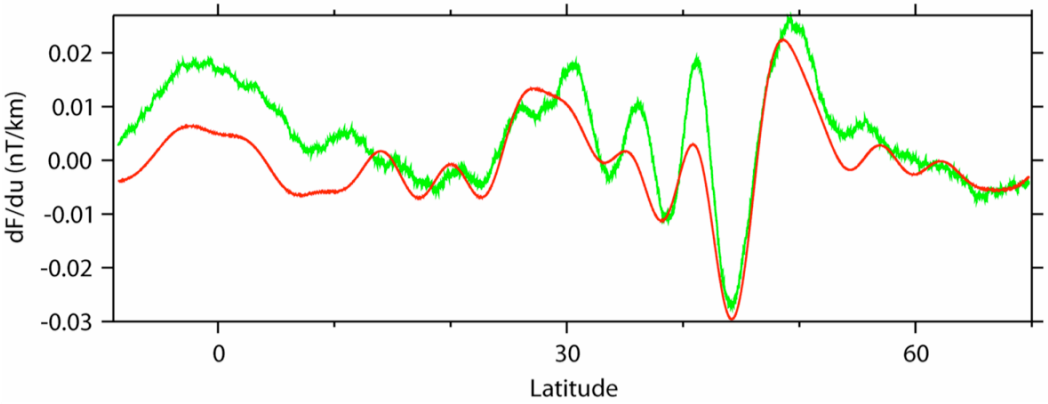


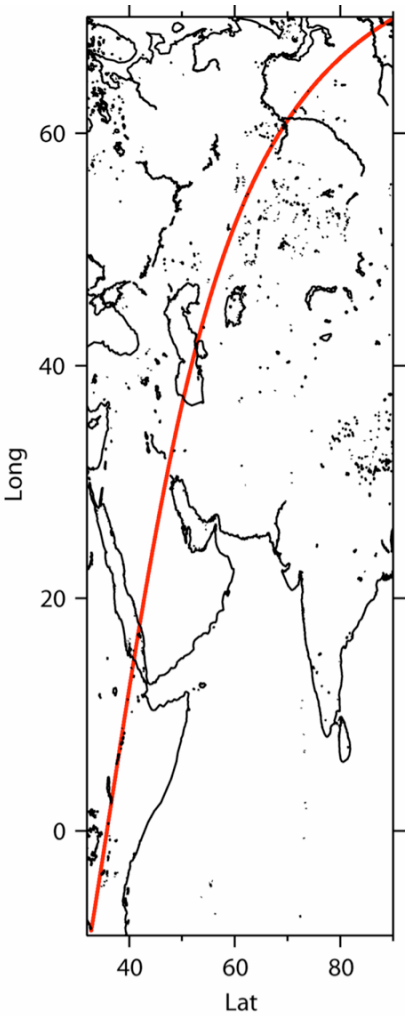
ST5 Observations of Magnetization of Earth's Crust – 2/2

Along-Track Gradient of the Crustal Magnetic Field



Green: SCMID Observations
Red: Comprehensive model (CM4) Model Prediction

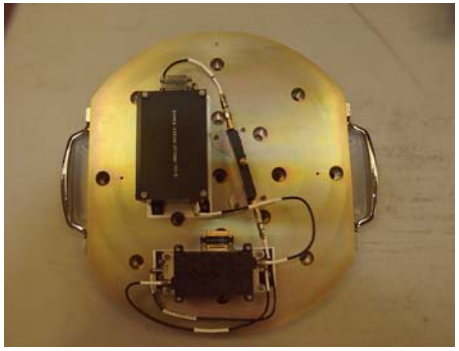




Backup

Miniature Communications Transponder

- **Technology partner: AeroAstro**
- **Description**
  - Provides coherent uplink and downlink
  - Low-power; low-mass; low-voltage
- **Key performance parameters**
  - Uplink 1 kbps; downlink 100 kbps
  - BER < $1x10^{-5}$ for downlink
- **Ground testing**
  - Component testing, compatibility testing, S/C I&T
- **Flight testing**
  - Used routinely throughout the mission
- **Future applicability: useful as-is, esp. with McMurdo or user-built ground station**



- Transponder Features:
  - Mass
    - Transponder = 862g
    - High Power Amplifier = 313g
    - Diplexer = 90g
    - Band Pass Filter = 150g
  - Power @ 7.2Vdc
    - Transponder
      - 3.9W (receive only)
      - 5.5W (transmit and receive)
    - High Power Amplifier (1.5W RF out)
      - 13W

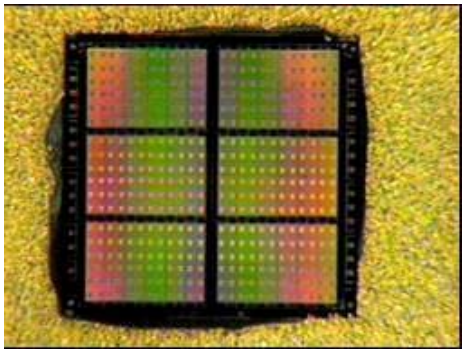
Cold Gas Micro-Thruster (CGMT)

- **Technology Partner:**
  - Marotta Scientific Controls
- **Description**
  - Can be operated in pulse and continuous fire modes
  - Low power; low leakage
- **Key performance parameters**
  - Specific impulse; thrust
- **Ground testing**
  - Component level
  - S/C I&T
- **Flight testing**
  - Used routinely for attitude maintenance
  - Delta-V maneuvers to constellation formations
- **Future applicability: useful as-is**

- **CGMT Features**
  - Mass = 78g (including lead wires)
  - Valve Characteristics @ 20°C
    - Minimum Drive Voltage = 2.5V
    - Coil Resistance = 1.3ohm
    - Coil Inductance = 500microH
    - Opening/closing response time <= 5 msec
  - Thrust > 2.1N @ 2000psi
    0.1N @ 100psi
  - ISP Level > 60sec
  - Leakage < $1x10^{-4}$sccs-He
  - Power = 2W @5.23Vdc
    (including thruster control electronics at maximum duty cycle)
  - Minimum Pulsewidth = 50msec
    (due to electronics design)

Variable Emittance Coating-MEMS

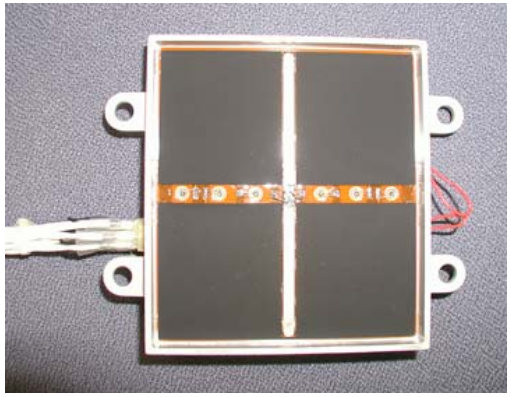
- **Technology partner:**
  - JHU Applied Physics Laboratory
  - Sandia National Laboratory
- **Description**
  - Micro ElectroMechanical Systems
  - Array of ultra-miniature shutters
- **Key performance parameters**
  - Range of emissivity variation
- **Ground testing**
  - Component-level
  - S/C I&T
- **Flight testing**
  - Demonstrated using 1.5W heater
  - Operated at least weekly to provide assessment of performance over time



- **MEMS VEC Features:**
  - Mass
    - Radiator = 56g
    - Controller = 212g
  - Power = 250mW @5.23Vdc
  - Actuation Voltage = 60Vdc
- **Future Applicability: Proof of concept for further development**

Variable Emittance Coating-ElectroStatic

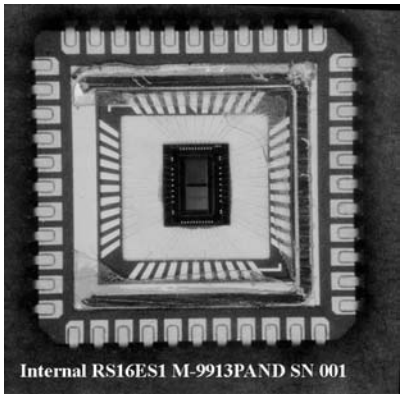
- **Technology partner: Sensortex**
- **Description**
  - Thermal control film made of composite metalized polymer
  - Changes between radiative or conductive heat transport via electrostatic forces
- **Key performance parameters**
  - Range of emissivity variation
- **Ground testing**
  - Component-level
- **Flight testing**
  - Demonstrated using 1.5W heater
  - Operated at least weekly to provide assessment of performance over time



- **ESR VEC Features:**
  - Mass
    - Radiator = 121g
    - Controller = 218g
  - Power = 310mW
    5.23Vdc
  - Actuation Voltage = 350Vdc
- **Future Applicability: Proof of concept for further development**

CULPRiT

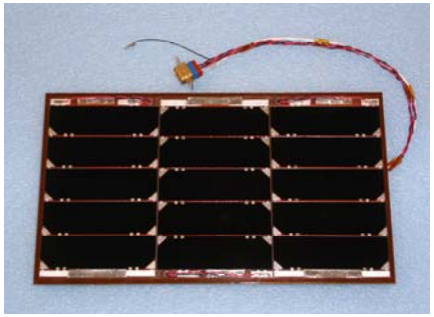
- **Technology Partners**
  - Center for Advanced Microelectronics and Biomolecular Research, University of Idaho
  - AMI Semiconductor
  - PicoDyne Inc.
- **Description**
  - Low-voltage CMOS technology
  - Radiation and latch-up tolerant
  - Used as Reed Solomon encoder
- **Key performance parameters**
  - Operating voltage
  - Degradation over time
- **Ground testing**
  - Radiation testing
  - C&DH component and I&T testing
- **Flight testing**
  - Used routinely; compared with conventional Reed-Solomon encoder on C&DH



- **ST-5 CULPRiT Features:**
  - Core Operating Voltage = 0.5Vdc
  - On-Chip 3.3Vdc Level Shifters
  - Internal active bias generation
  - Radiation tolerance:
    - Total Ionizing Dose >100kRads
  - Single Event Upset: LETth~20MeVcm^2/mg
- **Future Applicability**:
  - Use as-is or scale to lower operating voltage
  - Useful for many digital applications

Low Voltage Power Subsystem

- **Technology Partners:**
  - Battery: AEA Technology Space
  - Solar Array: Emcore
- **Description**
  - Triple junction solar cells
  - Lithium Ion Battery
- **Key performance parameters**
  - Battery capacity, orbital avg. power
- **Ground testing**
  - Component testing; S/C I&T
- **Flight testing**
  - Used routinely throughout the mission
  - Assessing degradation over time
- **Future applicability:**
  - Solar array and battery useful as-is or scalable



- **Battery Features:**
  - Mass = 645 g
  - Size = 12.7 cm x 6.5 cm x 8.6 cm
  - Voltage = 8.4Vdc (max)
  - Effective Capacity = 7.5A-h (to 6Vdc C/2 discharge)
- **Solar Array Features:**
  - 8 panels per spacecraft
  - 15 solar cells per panel
  - 3 strings (of 5 cells each) per panel
  - Panel dimensions: 16.5 cm x 28.6 cm
  - Raw Cell Efficiency: 28% average
  - Beginning of Life Electrical output per panel (30^{o}C, 1 Sun Air-Mass Zero):
    - load voltage = 10.2Vdc
    - current = 1.16 amps

Miniature Magnetometer

- **Technology Partner: UCLA**
- **Description**
  - Research-grade flux-gate magnetometer
  - High resolution, high precision, three-axis magnetic measurements
- **Key performance parameters**
  - Resolution, accuracy
- **Ground testing**
  - Component testing
  - S/C I&T
- **Flight testing**
  - Attitude determination
  - Science validation
- **Future applicability: useful as-is**

Features:

- Dynamic Range
  - 0 to +/- 64,000 nT, low sensitivity/full range
  - 0 to +/- 16,000 nT, high sensitivity/low range
- Intrinsic Noise < 0.1nT rms @ 1 Hz bandwidth
- Digital Resolution
  - Better than 0.25 nT in164,000 nT field
  - Better than 0.2 nT in 1,000 nT field
- Data Rate
  - 16 Vectors per second
  - simultaneous 17bit per axis data sample
- Power = 570mW @7.2Vdc
- Mass
  - Sensor Head: 55g
  - Electronics: 550g
- Size
  - Electronics Unit: 10 cm x 12 cm x 7.6 cm
  - Sensor Head: 5 cm x 5 cm x 3 cm

Evolved X-Band Antenna

- **Technology Partners**
  - NASA Ames
  - NMSU
- **Description**
  - Wire form
  - Designed using tree-structured computer algorithm
  - Candidate designs evaluated using fitness function
  - Does not require matching network
- **Key performance parameters**
  - Gain, VSWR
- **Ground testing**
  - Component-level testing with s/c mockup; S/C I&T
- **Flight testing**
  - Used routinely throughout the mission

- **Evolved Antenna Features**
  - Potential for high gain across a wider range of elevation angles
  - Pattern optimized for new orbit
  - Easy manufacturability
  - Low cost
- **Future applicability**
  - Demonstrates usefulness of computer algorithm for designing antennas